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FEASIBILITY STUDY OF DEVICE SYNTHESIS OF NON-LINEAR FILTERS.(U)

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UNIVERSITY OF SOUTHERN CALIFORNIA

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Efforts to date have shown that with careful tailoring to the problem at hand and by taking maximum advantage of recent advances in parallel/pipeline array processor architecture, the nonlinear filter is a practical estimation technique. The computational effort is significantly greater than for conventional linear or linearized (e.g. extended Kalman filtering) techniques, but the performance advantage may be significant where the observation is a significantly nonlinear function of the estimated states, and/or where

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) the observation noise (or plant noise) is significantly non-Gussain. The research has concentrated on the phase estimation problem which has proven to be an ideal test problem. However, with the techniques that have now been developed and proven, it is appropriate to consider a larger class of problems. Potential applications should meet the following criteria: 1) Performance advantages are of significant economic value 2) Observations are essentially nonlinear functions of the states that have to be estimated where the linear filter leads to unacceptable performance 3) Measurement (or state) noise is highly non-Gussain. An excellent example meeting all the above criteria would be the ELF communications problem. Other examples occur in deep space communication and in detection and tracking problems in general.

A

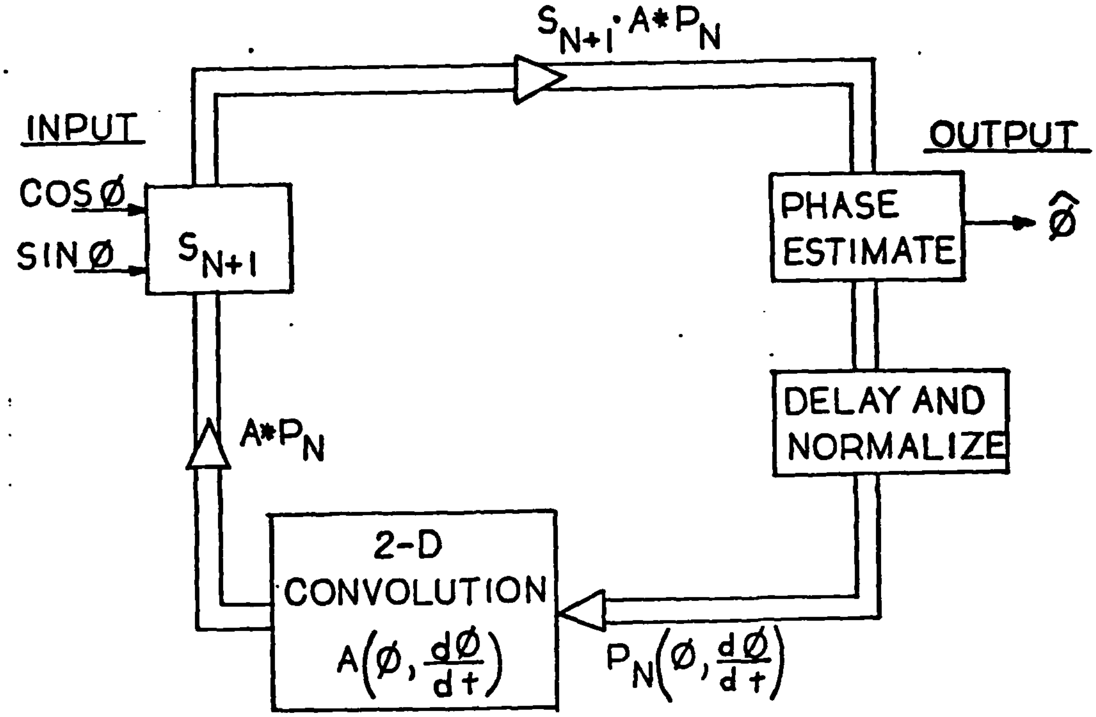
I. INTRODUCTION

The real time realization of the non-linear filter can have significant impact on military systems where a few db increase in sensitivity can result in a significant reduction in antenna size or required orbited weight. The filter cost can be more that offset by other system cost reductions. The object of our work is the realization of the non-linear fillter in real time by all-digital schemes and by hybrid optical-digital schemes.

II. Hybrid Optical-Digital

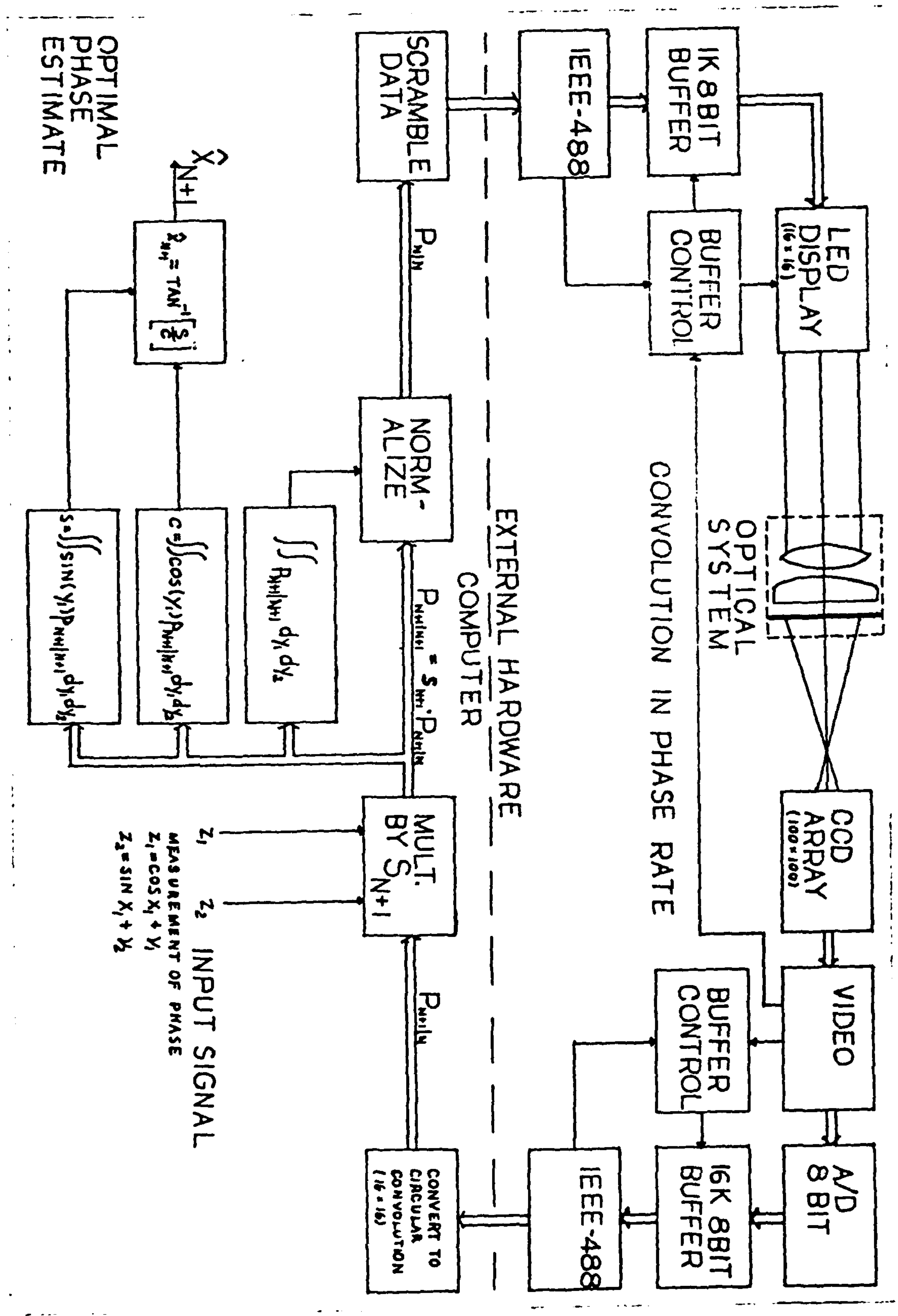
The non-linear phase estimator has limited real time applications because for each iteration, a first order convolution of a sizable second order matrix has to be computed. A hybrid approach where the convolution is handled optically and the rest of the computations are handled in a PDP-11 minicomputer is examined in this part of the project. Using this approach, the inherent 2-D property of optical processing is used to reduce the computation time of the convolution.

An experimental estimator that filters a demodulated coherent phase signal contaminated by white noise has been built and is shown schematically in Figure 1A&1B. Circulating in the computing loop is a two-dimensional probability density $p_n(\phi, d\phi/dt)$ in phase ϕ, and phase rate $d\phi/dt$. On each iteration around the loop, p_n is optically convolved with a 2-D gaussian $A(\phi, d\phi/dt)$. This gaussian is the probability density of the state noise in phase and phase rate. The resulting convolution is the multiplied by S_{n+1} which is calculated in each iteration from new incoming



COHERENT PHASE DEMODULATOR

FIGURE 1A



IK 8BIT BUFFER
IEEE-488
SCRAMBLE DATA
LED DISPLAY (16×16)
BUFFER CONTROL
OPTICAL SYSTEM
CONVOLUTION IN PHASE RATE
CCD ARRAY (100×100)
VIDEO
BUFFER CONTROL
A/D 8 BIT
16K 8BIT BUFFER
IEEE-488
CONVERT TO CIRCULAR CONVOLUTION (16×16)
EXTERNAL HARDWARE COMPUTER
NORM-ALIZE
MULT. BY S N+1
INPUT SIGNAL
MEASUREMENT OF PHASE
OPTIMAL PHASE ESTIMATE

FIGURE 1B

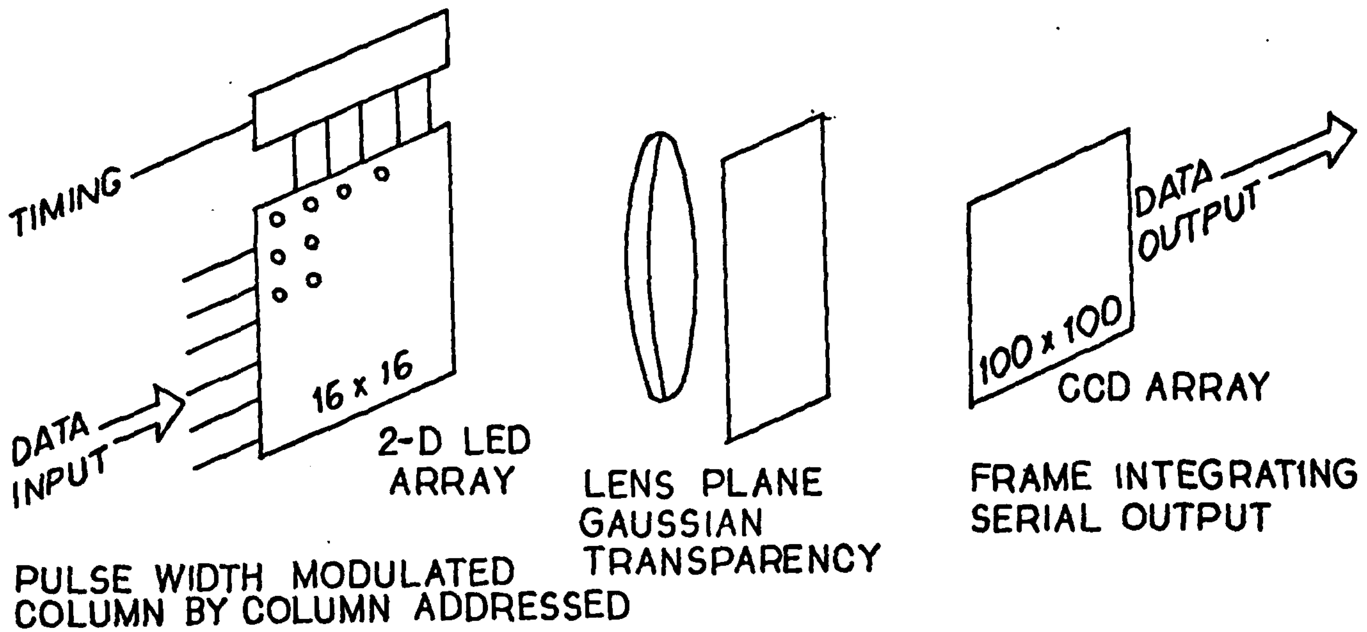
observations, $\cos\phi$ and $\sin\phi$. At this point the best estimate of the phase, $\hat{\phi}$, is extracted from p_{n+1}. On each iteration, p_n is updated by noisy incoming data, processed, and an optimal phase estimate is computed.

Since the probability densities are positive and real, an incoherent optical scheme can be used. This scheme is shown schematically in Figure 2. This has the advantage of eliminating interference and speckle problems. p_n is read into a 16 x 16 array of light emitting diodes (LED's) by the minicomputer. The data is pulse width modulated and illuminated one column at a time. An eight bit modulation scheme is used with a minimum pulse width of 2 usec. The LED pattern is convolved with the 2-D circular gaussian transparency in the lens plane. The convolution is detected by a 100 x 100 CCD array which integrates over the illumination cycle of the LED's. The data is serially read out of the CCD and via an A/D converter is read back into the minicomputer for further processing.

The details of optical system, the digital interfaces and the software are given in the annual reports and in the Ph.D. thesis of Dr. William E. Stephens, ("An Experimental Hybrid Optical-Digital Realization of the Coherent Phase Demodulator").

Performance of Optical Convolver

Measurements were made comparing the accuracy of the optically generated convolution to the digitally generated convolution. The optical convolution generated approximately 8 percent error. This error is 20.48 quantization levels or 4.36 bits of error which



INCOHERENT OPTICAL 2-D CONVOLVER

FIGURE 2

corresponds to 1.1 places of accuracy. Most of the error is generated from the nonuniformity in the LED intensity while the rest of the noise is inherent in the sensor and the electronics. A crude estimate of the signal to noise ratio for the optical convolution can be calculated by

$$S/N_{DB} = 20 \log \left[\frac{\text{max. signal value}}{\text{max. error value}}\right]$$

$$= 20 \log \left[\frac{256}{20.48}\right] = 21.94 \text{ DB}$$

Table 1 contains a summary of the performance of the optical convolution.

Performance of the Hybrid Filter

The performance of the hybrid filter was measured by a signal tracking test and a monte carlo evaluation. The signal tracking test was used to generate the raw data for the monte carlo evaluation and to examine in detail how the hybrid filter estimates vary from the estimates of a 16 x 16 digital filter and the estimates of a 32 x 160 digital filter. All versions were run using the same input sequence. The monte carlo evaluation measured the statistical reduction in noise of all versions of the filter for 2000 independent samples.

The 16 x 16 conditional probability density matrix of the optimal filter limits the usable signal to noise ratio range. The parameters used in the experiments are c = 0.3333 where c is the fraction of the filter time constant, N/S = 0.175 DB where N/S is the noise to signal ratio, σ_{sq} 2 = 0.5 where σ_{sq} 2 is the variance of the gaussian point spread function and q = 1.0 radians where

TABLE I

SUMMARY OF OPTICAL CONVOLUTION

Speed

5.2 sec averaging method

19.7 sec spline raduction method

Noise

hardware quantization error

$< 3.906 \cdot 10^{-3}$

dark current

19 mV at -13 C

reduced to $< 3.906 \cdot 10^{-3}$ by biasing technique

thermal noise

$5 \cdot 10^{-3}$ V

total sensor error

$< 14.330 \cdot 10^{-3}$

LED Error

$75.3 \cdot 10^{-3}$ (population deviation)

Gaussian Error Measurement

$-80.0 \cdot 10^{-3}$

Signal to Noise Ratio

$S/N_{DB} = 21.94$ DB

q is the variance of the state covariance matrix. All other constants can be calculated from the given parameters. The calculated paramenters are $\Delta = 0.4256$ where Δ is the time between samples and $r = 0.6647$ radians where r is the variance of the measurement covariance matrix.

Many tracking tests were performed on the hybrid filter and digital filters. The same psuedorandom number generator sequence was used in all tests so that there is a basis of comparison between the filter estimates. Each test consisted of a 300 iteration run or a 600 iteration run. The filters tested were the hybrid optical-digital filter with an averaging reduction scheme, the hybrid optical-digital filter with a spline reduction scheme, the digital filter with a 16 x 16 matrix and the digital filter with a 32 x 160 matrix. As previously noted, the hybrid filters both use a 16 x 16 matrix representation of the conditional density.

A summary of the Monte Carlo simulation is given in Table 2. We consider the linearized version of this phase locked loop as a basis of comparison. If we implement a non-linear version of this estimator we can improve the signal to noise ratio on the output by 2.55 db. This is the best possible signal to noise ratio with the given input parameters. The hybrid system using averaging reduction improved the S/N by 2.31 db and the hybrid system using spline reduction improved the S/N by 2.42 db. Thus although the optical convolver is not nearly as accurate as the digital convolver (8% error), this does not have a serious effect on the overall filter performance. <u>The hybrid spline reduction filter is only 0.13 db noisier that the optimum digital filter</u>.

TABLE II

MONTE CARLO SIMULATION

Monet Carlo Simulation Parameters

$N/S = 0.175$ DB $c = 0.3333$ $\Delta = 0.4256$ $q = 1.0$ $r = 0.6647$

Total Iterations = 6030   Independent Samples = 2010

Measured Population Variance of Demodulated Input Signal

Input Signal	1.7512
High Confidence Interval	1.9342
Low Confidence Interval	1.5998

	Output Population Error Variance (radians)	High Conf. Int. (radians)	Low Conf. Int. (radians)	Improvement from Linearized Filter	Change in N/S_{DB}
Linearized Kalman Filter of PLL	2.2649	2.5016	2.0691	——	——
Digital 16 × 16 Nonlinear Filter	1.2584	1.3900	1.1496	1.0065	-2.55
Hybrid Averaging Reduction Nonlinear Filter	1.3318	1.4710	1.2166	0.9331	-2.31
Hybrid Spline Reduction Nonlinear Filter	1.2960	1.4315	1.1840	0.9689	-2.42

The expectation of substantially reduced filter iteration times with the hybrid filter cannot be fully realized because of the required interface times between the digital and optical portions of the loop. In our experiments we did not attempt to minimize interface times but only to show feasibility of the system. Based on our experience we can estimate a minimum loop iteration time using optimum interface architecture.

As shown in Table 2, the iteration time for the experimental hybrid filter was 5.240 sec. The minimum iteration time with optimum interfacing is estimated to 92 msec.

An All Optical System

The obvious way to avoid the interface problems and to increase the loop iteration time is to go to an all optical realization of the estimator. This is presently not technically possible and requires the development of new optical devices. Several suggestions for an all optical system are given in the Ph. D thesis of William E. Stephens.

III. ALL DIGITAL PART

When the contract started, we had a curve of error variance vs. signal to noise ratio for the 2-D phase demodulation problem based on 200 sample functions each of length 130 time steps. The curve was constructed of points each of which required four hours of CD.C 6600 time, roughly 550 msec. per timepoint.

At the outset of the contract, we determined that our computational requirements could best be satisfied by the acquisition of a Floating Point system AP-120B array processor. With the help of Dr. Randy Cole of USC-ISI, we coded our nonlinear filtering problem (i.e. phase demodulation) in AP 120B assembly language and achieved a 6 fold speedup over the 6600 time. Later we gained another factor of 2 by redesigning the loop to separate row and column operations in two sub-blocks. This last increase was obtained by following a suggestion of Dr. K.D. Senne of Lincoln Laboratory. When the AP 120B was delivered to U.S.C., its acceptance test was to match CDC 6600 output for the nonlinear filtering problem. After delivery, massive Monte Carlo runs were made at 12 signal to noise ratios, these had a precision of $\pm$ .034 db, and allowed a precise performance comparison with the usual linear design and phase lock loop. Figure 3 summarizes these results see also [4]. During this period we also participated in the planning and design of the optical convolver.

Previously, we had experimented with the 3 dimensional combined phase and amplitude demodulator at the Institute for Computation for Science and Engineering at NASA Langley, see [9] for details, where a program realizing the 25,000 point mass nonlinear filter was developed and tested on the CDC STAR 100. We

PERFORMANCE IMPROVEMENT OF AN OPTIMAL DEMODULATOR

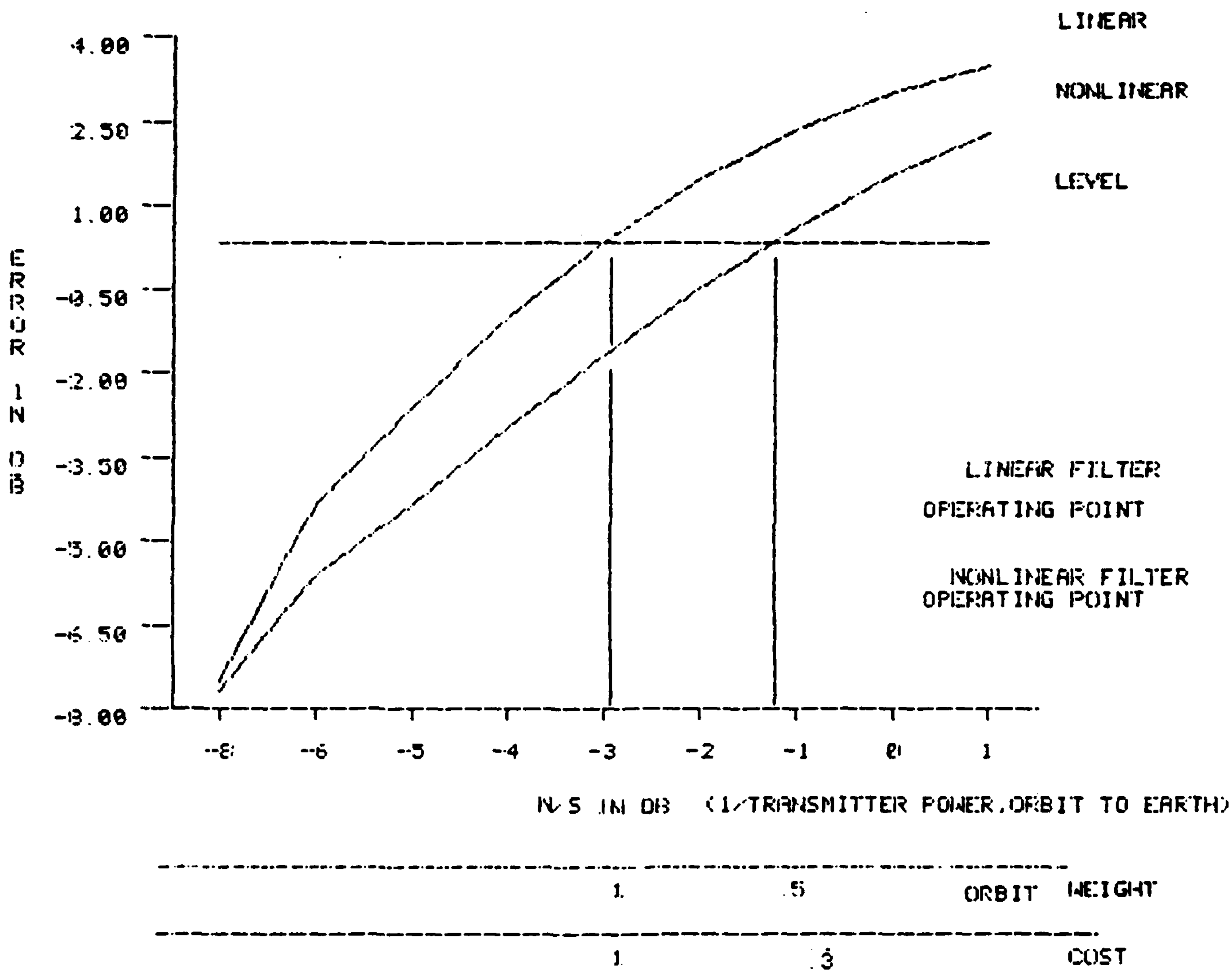


FIGURE 3

decided to code this filter on the AP 120B. Because 30,000 Monte Carlos required 30 days of AP 120B cpu time, the program which we developed and checked out against the STAR 100 and the CDC 7600, 6 place estimate agreement had to be made restartable. The systems programming for our host to achieve restartability was done by Dr. Milton Campbell of Syscom Design as a consultant. The software we designed was within 20% of the ideal performance of the AP 120B. The software for this and other machines is fully documented in 5 . We proceeded over a period of one and a half years to run Monte Carlos at 10 separate signal to noise ratios, logging 300 days of AP 120 CPU time. From these results we found a remarkable phenomenon, see [1] , namely that under certain circumctances more amplitude uncertainty could achieve better phase estimation. This latter phenomenon was analyzed in some of the interim reports. The joint information between phase and the observations was also computed for various levels of amplitude uncertainty was also Monte Carloed giving another handle on understanding the phenomenon.

Problems of phase demodulation fall into two categories, 1) relative phase is the important quantity and 2) absolute phase estimation. The results previously described deal with the problem of relative phase estimation. During the last couple of years we have investigated the problem of absolute phase demodulation and our results are given in [2] and [3] . In these studies Professor J.F. Moura of Instituto Superior Technico in Lisbon was able to participate with the support of a NATO grant. Our problem here was concerned with cycle slipping by an optimal phase estimator where the phase was modelled as a 1 dimensional markov process. As the computational task was immense, we were restricted to a 1 dimensional model. Our results were the design of an optimal nonlinear absolute phase estimator which not only tracked well, but slipped cycles 20% less than the classical linear design.

We have also developed a graphics capability in order to display the real time evolution of the condition density of signal given the observations. The solution of the nonlinear filtering problem as observations accrue, can be seen in color. Large amounts of graphics software have been developed so that the densities computed on the AP 120B can be imaged in color on the Chromatics high resolution CRT and black and white hardcopy on an Anadex printer can be obtained. The CRT screen produces color hardcopy as a photographic 35 mm color slide. We have a large library of color density slides.

In parallel, we were conducting studies on various supercompters to understand the impact of architecture on the computational task inherent in the nonlinear filtering problem. The machines investigated and benchmarked after extensive software development were Cray 1, Illiac, CDC 7600, CDC 6600, PDP 10, PDP 11-70, STAR 100 and VAX. Lincoln Laboratory allowed Dr. K.D. Senne to spend part of his time on this project. Detailed results here can be found in [4].

Finally, we helped with the comparison of the optical convolver and the all digital realization by providing suggestions as to how to measure accuracy, etc.

Summary of Status and Prospectus

Our efforts to date have shown that with careful tailoring to the problem at hand and by taking macimum advantage of recent advances in parallel/pipeline array processor architecture, the nonlinear filter is a practical estimation technique. The computational effort is significantly greater than for conventional linear or linearized (e.g. extended K-B) techniques, but the performance advantage may be significant where the observation is a significantly nonlinear function of the estimated states, and/or where the observation noise (or plant noise) is significantly non-Gaussian.

Our efforts to date have concentrated on the phase estimation problem for the reasons mentioned earlier. This has proven to be an ideal test problem however, with the techniques that have now been developed and proven, it is now appropriate to consider a larger class of problems.

Potential applications of all those meeting the following criteria:

1) Performance advantages are of significant economic value

2) Observations are essentially nonlinear functions of the states that have to be estimated where the linear filter leads to unacceptable performance

3) Where measurement (or state) noise is highly non-Gaussian.

An excellent example meeting all the above criteria would be the ELF communications problem. Other examples occur in deep space communication and in detection and tracking problems in general for example AWACS.

IV. PERSONNEL SUPPORTED

A. Principal Invesitgator - W. H. Steier and B. S. Bucy

B. Research Associates - R. E. Joiner, C. P. Christensen and S. Park

C. Consultants - Dr. A. J. Mallinckdrodt of Communitations Research, provided software development,

Dr. Milton Campbell of Syscom Design, systems programming.

D. Technical Typist - Illse Allott

E. Research Assistants - Faramarz Ghovanlou, Tom Blakney, Humberto Tomes, William E. Stephens, Chris Sexton, Howard Barr, David Drake and Robert Hoffman

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